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# Effect of Fuel Composition and Post-Combustion Chamber length on Combustion Performance of Paraffin-based Hybrid Rocket Motor

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## Abstract

With $H_2O_2$/paraffin-based fuel as the propellant, the effects of fuel composition and post-combustion chamber length on combustion performance of hybrid rocket motor have been experimentally investigated. Since the mechanical strength of pure paraffin wax or paraffin-based fuel mixed with HTPB cannot satisfy the requirements of practical application of hybrid rocket motor, additives to pure paraffin fuel are necessary to enhance the mechanical property of paraffin-based fuel. It shows that the mechanical strength of paraffin-based fuels can be effectively enhanced by adding a variety of additives such as polymer waxes, hardeners, tackifier, etc. Regression rate of the paraffin based fuel with additives were then measured in the present work using a lab scale hybrid rocket motor. Experimental results have been compared with data of regression rate found in literature and with HTPB fuel. It is found that this novel fuel proposed in the present work has a much higher regression rate than traditional solid fuel (HTPB). In addition, by changing the length of post-combustion chamber, the effect of the length of post-combustion chamber on the combustion performance of paraffin-based fuel hybrid rocket motor has been investigated. The results show that even though fuel consumption increased with a shorter post-combustion chamber length, there are no significant differences in thrust and combustion pressure, meaning that the increase of post-combustion chamber length can effectively improves the combustion performance of hybrid rocket motor.

**Keywords**: *Hybrid Rocket Motor, Paraffin-based Fuel, Regression Rate,*

## 1. Introduction

Hybrid Rocket Motor (HRM) refers to rocket propulsion system that uses both solid fuel and liquid oxidizer as propellants. HRM has multiple advantages compared to solid and liquid rocket motor such as high safety, simplicity, cost effectiveness, adjustable thrust and capability of shut-down or restart, making it a promising technology in various space missions. However, although long known, this kind of propulsion never draw much interest in the past, partially due to its low regression rate with polymers commonly used as combustibles like HTPB (hydroxyl-terminated poly-butadiene). To realize a higher thrust, fuel grain with multiple ports is necessary which results in a low volumetric efficiency. Various investigations have been performed to increase the regression rate of hybrid rocket motor among which using paraffin-based hybrid rocket motor is a possible alternative for large thrust hybrid rocket motor applications. It has been found that the regression rate of paraffin-based fuel is 3-5 times higher than that of conventional fuels due to its low melting point. However, pure paraffin and paraffin mixed only with HTPB or Polyethylene Wax have a poor mechanical characteristic that cannot meet the requirement of practical applications [1]. Additives are necessary to ameliorate the mechanical properties of paraffin-based fuel grains to avoid surface and internal rips, defects, micro-cracks and other microstructure discontinuities. Consequently, the first objective of the present work

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is to investigate the effect of composition variations on mechanical characteristics and thermodynamic properties of paraffin-based solid fuel. A lab scale hybrid rocket motor has been used to perform fire test for paraffin-based fuels containing different components of additives.

Another open issue related to hybrid rocket motor is the lower combustion efficiency due to its intrinsic properties that the combustion happens only in the boundary layer of the oxidizer flow and it leads to the formation of a detached flame region over the solid combustible surface [2]. A common approach to improve combustion efficiency is to install a post-combustion chamber where enhancing the mixing of fuel/oxidizer and extending burning time. Other ideas are to place a mixer in the first part or in the middle of the fuel grain. Nevertheless, a resume of literature reveals that the aforementioned investigations are mainly concentrated to numerical results [3, 4]; experimental investigations of effects of adding bluff body, diaphragm or changing combustion chamber size on the combustion performance are still limited. Hence, the other objective of the present work is to experimentally investigate the effect of combustion chamber size, adding bluff body, diaphragm in different location on the performance of paraffin-based hybrid rocket motor.

Therefore, the objective of the present work is two-fold: firstly, a new paraffin-based fuel consisting of hardening agent, tackifier, plasticizer and carbon powder is proposed by considering the trade-off between amelioration of mechanical strength and remaining the advantage of high regression rate of paraffin-based solid fuel. Series of fire tests are performed with different fuel grains using a lab-scale hydrogen peroxide/paraffin rocket motor. The regression rate of the proposed paraffin-based fuel will be measured and compared with literature; secondly, hybrid rocket motors with different combustion chamber length and mixers are tested to investigate the effects of combustion chamber length and adding mixers (a bluff-body and swirl-blade) on combustion performance of paraffin-based hybrid rocket motor.

## 2. Experimental set-up

The experiments were conducted using a lab scale hybrid rocket motor with paraffin-based fuel and hydrogen peroxide as the propellant. As illustrated in Fig 1, the test facility consists of 3 major subsystems: plumbing, control and instrumentation. In the plumbing part, two fluids are used i.e. hydrogen peroxide serves as the oxidizer and series of valves, storage tank and handling components have the purpose of delivering the $H_2O_2$ to the combustion chamber;. $N_2$ has multiple uses, the primary of which is used to pressurize the hydrogen peroxide tank and it also serves as a combustion chamber purge, quenching combustion after a test or in the event of a test abort, finally it is used to actuate all ball valves in the plumbing system. For safety consideration, the $H_2O_2$ tank and delivery lines are connected to a pool of water. In case of leakage or spill occurs, the water will dilute the $H_2O_2$ quickly into a harmless concentration. The whole system is controlled remotely and experimental data including pressure at different locations and the thrust are acquired by LabVIEW. The data acquisition frequency is regulated to 100Hz.

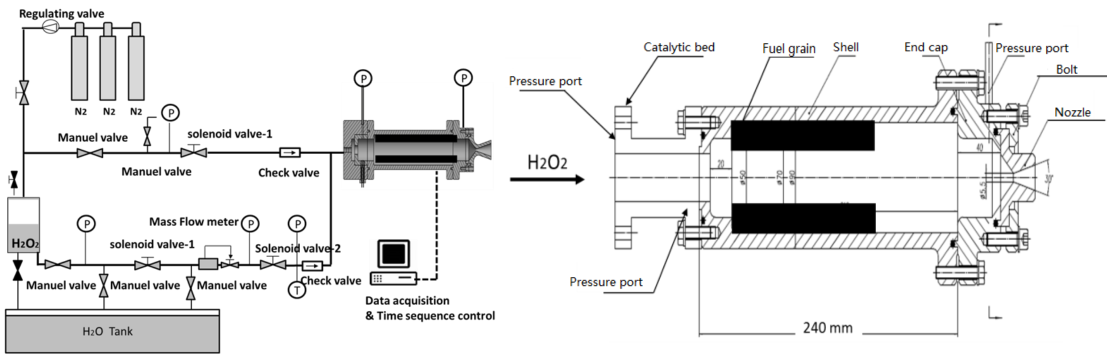


**Fig 1.** Left: Test facility schematic; Right: Experimental hybrid rocket motor configuration

Fig 1 (right) shows the experimental hybrid rocket motor configuration. With a catalytic bed at the head (internal multi-layered silver grid), the length of the main combustion chamber of the HRM used in the current work is 240 mm, the lengths of the fore-end and aft-end combustion chambers are 20 and 40 mm. The outer diameter of solid fuel grain is 70 mm. The hydrogen peroxide flow rate was controlled to 43 g/s, so the total flow rate with solid fuel was controlled to around 50 g/s. A conical nozzle made of red copper with a diameter 5.5 mm is used in the present work. Four pressure sensors are located at fore and aft end of the catalytic bed and combustion chamber to monitor the pressure variation during the fire test.

## 3. Experimental results

### 3.1. Effect of fuel composition

The amelioration of mechanical strength of paraffin-based solid fuel was investigated by adding polymer waxes, hardeners, tackifier and carbon powder in pure paraffin. It is found that these additives can effectively increase the mechanical strength of paraffin-based fuel grains. However, as the regression rate of additives is usually lower than pure paraffin, the quantity of additives should be carefully controlled by considering the trade-off between mechanical strength and its high regression rate property. In the present work, as illustrated in Table 1, three different fuel mixtures having satisfied mechanical strength were tested using aforementioned hybrid rocket motor. Pressure variations in combustion chamber of these three different fuels are plotted in Fig.2.

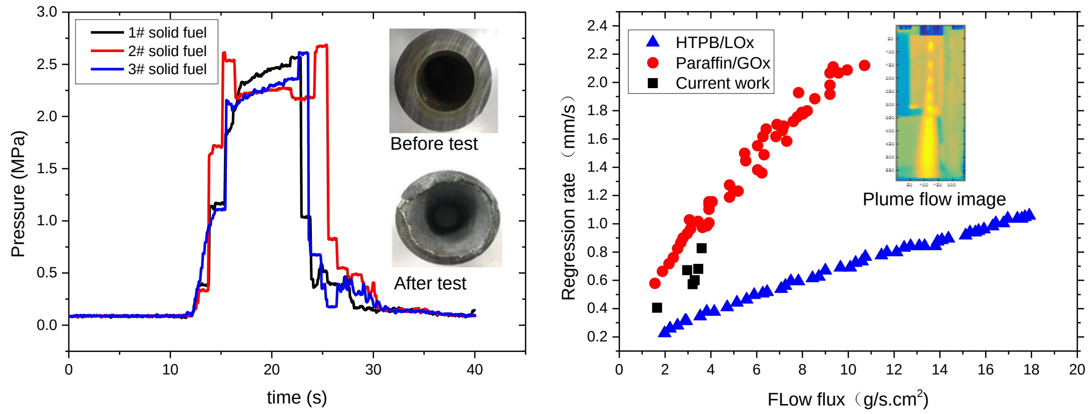


**Fig 2.** Left: Pressure of combustion chamber with different components of paraffin-based fuel. Right: Comparation of the regression rate of propellant used in this paper, HTPB/LOX and paraffin-based fuel/GOX.

**Table 1**. Composition of solid fuel used in the present work

| No. | Paraffin | Tackifier | Carbon | Hardener | PE wax |
|---|---|---|---|---|---|
| 1# | 50% | 18% | 2% | 10% | 20% |
| 2# | 20% | 18% | 2% | 10% | 50% |
| 3# | 0% | 18% | 2% | 10% | 70% |

It shows that solid fuel 2 and 3 have similar performance, meanwhile solid fuel 1 containing 50% (wt) paraffin, 20% PE and 18% tackifier, 2% carbon and 10% hardener agents have a higher combustion pressure. In order to evaluate the regression rate of this novel paraffin-based fuel, a total of 10 fire tests were conducted. The regression rate was calculated by utilizing the differential method [6]. The experimental results obtained in the present work are compared with literature found results**.** It shows that the regression rate of solid fuels used in the present work is much higher than that of HTPB. Meanwhile, it's slightly lower than that of paraffin-based fuel shown in the reference, with GOX as the oxidizer. Fig 2 also illustrates the inner and outer surface of the novel fuel grain before and after the fire test. It can be seen that the surfaces of solid fuel is smooth and crack-free after burning test. This result could effectively indicate that the mechanical strength of this novel solid fuel can satisfy the requirements of lab-scale hybrid rocket motor fire test.

### 3.2. Effect of combustion chamber length

In order to clarify the effect of post-combustion chamber length on the combustion performance of HRM, three different sizes of solid fuel grains were selected with lengths of 100 mm, 175 mm, and

210 mm, consequently, the size of post combustion chamber will change. Fig 3 shows that, interestingly, there is no significant difference in the thrust and combustion chamber pressure in spite of using fuel grains of different lengths. The results indicate that with a longer post-combustion chamber length, for the same performance of hybrid rocket motor the fuel consumption decreased, thus giving ameliorations in specific impulse.

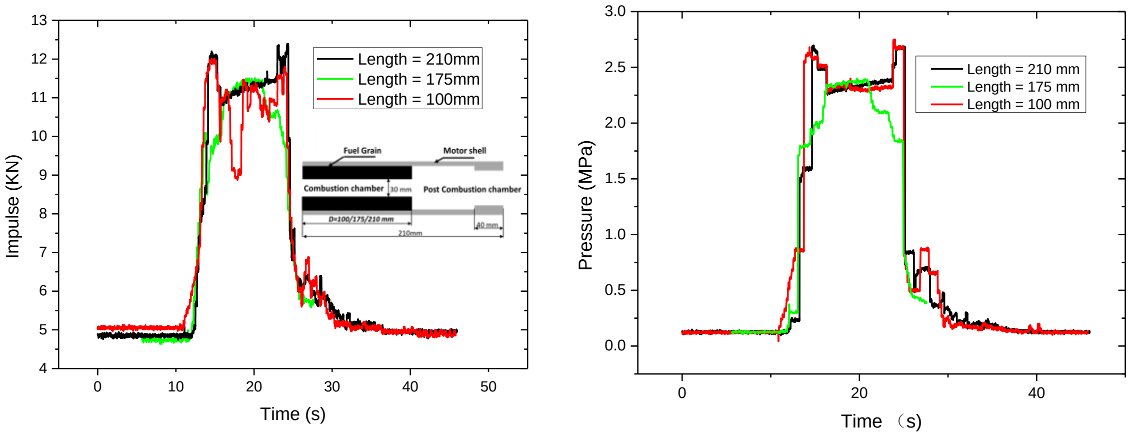


**Fig 3.** Parameter performance at different lengths of fuel grains. Left: thrust; Right: combustion chamber pressure

## 4. Conclusion

In this paper, testing has been conducted to investigate the effect of solid fuel composition and post-combustion chamber size on the performance of combustion of a lab-scale paraffin-based hybrid rocket motor. A series of fire test have been conducted and it shows that the addition of tackifier, hardeners, polymer waxes, and carbon powders can effectively enhance the mechanical strength of the paraffin-based fuel. Moreover, the regression rate of this novel fuel is 2-3 times higher than that of HTPB fuel. Also, the size of post-combustion chamber plays a crucial role in the combustion performance of the hybrid rocket motor with mixing enhancement and burning time extended. Experiment results indicate that with a longer post-combustion chamber length, for the same performance of the hybrid rocket motor the fuel consumption decreased, thus giving ameliorations in specific impulse.

## References

1. Cardoso K P, Ferrão L F A, Kawachi E Y, et al, C.: Preparation of paraffin-based solid combustible for hybrid propulsion rocket motor. Journal of Propulsion & Power, 33(2), 1-8(2016).
2. Karabeyoglu M A, Altman D, Cantwell B J, C.: Combustion of liquefying hybrid propellants: part 1, general theory. *Journal of Propulsion & Power, 18*(3), 610-620(2015).
3. Cai G, Li C, Tian H, C.: Numerical and experimental analysis of heat transfer in injector plate of hydrogen peroxide hybrid rocket motor. Acta Astronautica, 128, 286-294(2016).
4. Cai G, Zhang Y, Tian H, et al, C.: Effect of grain port length–diameter ratio on combustion performance in hybrid rocket motors. Acta Astronautica, 128, 83-90(2016).
5. Karabeyoglu A, Zilliac G, Cantwell B J, et al, C.: Scale-up tests of high regression rate paraffin-based hybrid rocket fuels. Journal of Propulsion & Power, 20(6), 1037-1045(2012).
6. Collard C, C.: Trade-off between paraffin-based and aluminium-loaded HTPB fuels to improve performance of hybrid rocket fed with N2O. Aerospace Science & Technology, 37(5), 81-92(2014).